# EXECUTIVE SUMMARY

· The scientific strategy of NASA's Astronomical Origins program call for a series of increasingly larger space observatories. A very attractive means to build, integrate, test, maintain and deploy many of these space-based observatories is to involve space construction with a combination of humans and advanced robots.

· If space construction were to become standard practice, it would mean the structures could be designed for the miniscule loads found on orbit, leading to savings in mass, efficiencies in the use of launch vehicles and the potential for repair, retrieval, servicing and upgrades. Observatories would be designed for the environment in which they will do their observations, rather the earth's gravity or launch loads.

· Space construction would mean structures could be integrated, tested, verified and repaired on orbit, thereby avoiding the prohibitive cost of extensive ground-based risk mitigation tests. Similarly, full access to a deployed observatory by humans and robots could result in more effective optical testing in space.

· This is an untapped–potentially an *enabling*– method for saving mass and cost of NASA's planned large space observatories.

· The relative role of humans and robots for the purpose of building and maintaining spacecraft will change, depending on the need and function of each mission.

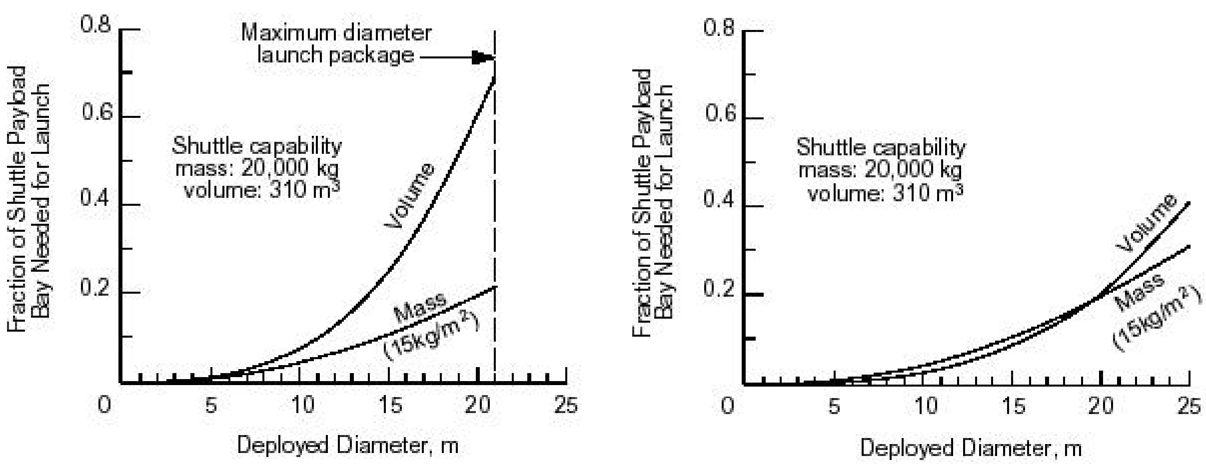
· Scientific progress will requite increases in collecting area for space-based observatories

· Each mission will define a set of human–robotic technologies and their ability to accomplish identified task primitive groups.

· Telescope assembly will enable more science

· The benefits of assembly are illustrated below. The figure compares the mass and volume demands of deployed (left) and assembled (right) large mirror assemblies. The assembled system more fully exploits the capacity of the shuttle. The final assembly will also have more structural performance than its deployed counterpart.

[From Launching a 25-Meter Space Telescope *Are Astronauts a Key to the Next Technically Logical Step After NGST?* Mark S. Lake *NASA Langley Research Center Hampton, Virginia 23681* Presented at the 2001 IEEE Aerospace Conference]



# ADVANCED REVOLUTIONARY CONCEPTS

## On-orbit Assembly

Mankind is only beginning to learn how to live and work in space. There is little question that men and machines will work together in space to construct, deploy, maintain and reconfigure systems even more complex than ISS. In many of these tasks it will be desirable to have human intervention while others are best left to robotic devices. Astronauts, working with robots, provide the potential for assembly, maintenance, servicing/repair and upgrading of a wide range of ambitious observatories being planned by NASA now.

Already, a number of studies have concluded that human and robotic assembly of large astrophysical observatories provides a number of important advantages, when compared with deployed systems. For example, a single shuttle launch can carry an entire 25 meter observatory, assuming that astronauts will assemble the structure.[1] Concepts for deployed observatories would be hard pressed to achieve this efficiency in the use of launch capability. Moreover, the product of the assembled system has superior structural properties, makes full use of both the volume and mass capability of the launch vehicle and, most important, is on a scalable path to even larger systems. The inherent packaging inefficiency of deployed systems severely limits their scalability.

Space construction is an essential next step in the human exploration and commercial development of space. NASA envisions a bold future of large space platforms, for commercial development, manned exploration, and astronomy. The ability to construct large telescopes in space would enable a near term leap in capability for NASA space science. All these missions share the common requirement for structures too large to integrate on the ground and too complex to package into a single launch vehicle. Several entities are already beginning to research this topic. For example, the journal Optical Engineering will be having a special issue on the subject of the future of large telescopes in space in August 2002 . Also, AURA (Associated Universities for Research in Astronomy) is doing a study on large space optics, including assembled versions. A large library of assembled observatory solutions resides in the archives of the Next Generation Space Telescope (NGST) web sites.

A key challenge for this vision is the ability to construct the structures for these platforms in orbit. Current practice for all spacecraft–from communication satellites to the International Space Station–is to largely integrate the structures on the ground, test them in space simulators and launch them in nearly their final configuration. This means that current space structures are primarily designed for 1-g testing and launch. This current state of practice, the standard for nearly 50 years, puts more mass in the structure than is required once the structure gets to orbit. Moreover, the next step chosen by NASA (as demonstrated by NGST) is the deployment of systems too large to be launched in their operational configuration.

If space construction were to become standard practice, it would mean the structures could be designed for the miniscule loads found on orbit. Today, this is only possible for the few shapes that can be efficiently deployed. More than saving mass, space construction would mean structures could be integrated, tested, verified and repaired on orbit. This would save the prohibitive cost of extensive ground-based risk mitigation tests. This is an untapped–potentially an *enabling*– method for saving mass and cost on future commercial and space missions, including NASA's planned large space telescopes.

Perhaps the most important component of the possible advantages of space assembly is that it will **drive** the industry to learn how to test on orbit. Right now, the compromises demanded by ground testing and survival of launch loads has allowed the industry to avoid the many (but manageable) challenges of testing in space. In discussing on-orbit testing, we take note that **functional** testing will still take place on the ground, so long as it is not a threat to the safety of the observatory. Most of the functional testing can take place in subassemblies that are stiff enough to be operated in 1G. The purpose of that testing will be to assure that the designed features of the subsystems meet requirements. Complemented by effective system modeling, the ground functional testing will give mission managers confidence that the system is ready for flight. Clearly, the whole concept of 'flight readiness' will be re-evaluated during the transition to this type of approach. In fact, NASA has a particular challenge to evolve its management approach, standards and evaluation criteria if it wishes a new approach to space missions to evolve.

Primarily, the advantages of space testing will benefit large astrophysical observatories. When the mass density of these observatories falls to a level consistent with on-orbit loads they will be very light, they will be unable to be tested on the ground. When testing in space is seriously considered, designers will realize that, for instance, the costs and complexity of simulating star-light on the ground will be eliminated, since real stars will become the sources of the test light. Testing in LEO will allow human intervention in the event that there is functional failure. Systems developed far in the future could also be tested out of LEO, such as at L2. NGST has already suffered some impact from these issues. The diameter of its primary mirror has been reduced from its intended 8 meters, at least in part as a concession to the difficulties of testing an optic that big in 1G.

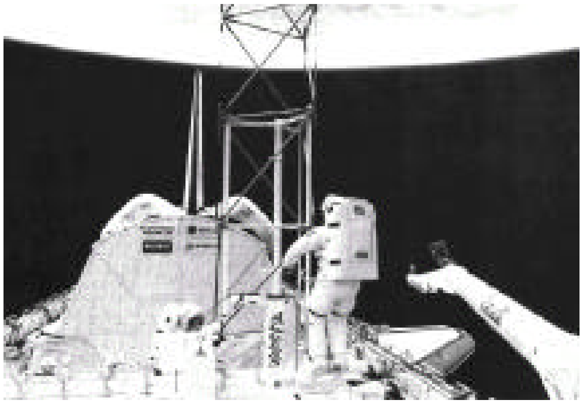
Of course, testing in LEO implies some significant technical challenges. The primary issue is thermal management of the system during testing. Since almost all large astrophysical observatories are intended for use at L2 or in heliocentric orbits, their testing in LEO will force them to be functional in an environment that is not consistent with their operational location. While smaller and much more dense telescopes (such as Hubble) have been operated successfully in LEO, the observatories of the future will have such low stiffness that **dynamic** stiffening will be required to accommodate the thermal environment in which they will be tested. This implies a great increase in technologies related to structural management. At the same time, virtually all of the observatories planned for the future will be equipped with sensors and actuators to allow them to manage their optical quality. That same technology can be exploited during the LEO testing phase to evaluate and calibrate the entire optical system **while the observatory is still accessible.** Both the structural and optical dynamic controls will demand substantial increase in the density and performance of both sensors and actuators, advances in modeling that will allow effective prediction of the performance of the structures management system and higher bandwidth in all flight components.

A breakthrough capability in the construction of space telescopes would naturally enable construction of other platforms for exploration and commercialization. Of the mix of envisioned future platforms, for space solar power, space stations, and commercial communications and observations, the telescope problem is possibly the most technologically rich. If NASA solves the telescope construction problem, it would also solve other, simpler construction problems. Construction of a telescope will likely be a considerably more delicate, more complex operation, requiring innovative structures, EVA operations, robotics, materials, and processes that would apply to these other applications. The converse is not necessarily true; that is, one could develop technology for the assembly of large space stations, and not necessarily address the issues that would enable future telescopes.

## Space Construction: A Key to the Future Development, Exploration and Commercial Development of Space

The earliest mention of space construction of which we are aware is Reference [2], by Soviet Cosmonaut Col. A. Nikolayev. There were other studies in the US of partial assembly of telescopes by astronauts, though references are hard to find.

**Figure 1 1985 ACCESS Experiment** The EASE/ACCESS flight demonstrated EVA construction. The **1987 Space Station Freedom Baseline** Freedom's truss was assembled by EVA/EVR



Space construction was first considered as a serious engineering study in the late 1970's.[3,4] It was motivated by the expected inexpensive access to space that would be provided via the Shuttle. Concepts were developed for very large platforms in orbit that would rely on construction in space. The early concepts for space solar power satellites and large communication satellites were some of these. In the 1980's, NASA investment in space construction was largely linked to the problem of constructing early concepts of the International Space Station. This research was embodied in the 1987 Space Station Freedom baseline

One of the engineering points of view that developed at this time in NASA, industry and academia, was that the most efficient structures for large space platforms might necessarily be assembled on orbit, not simply deployed. It was recognized that, from the point of view of cost, mass and packaged density, the best arrangement of material to form structures in space would probably be ones assembled and integrated there, rather than ones integrated on the ground and deployed. This was dictated by mechanics and material physics, more than any other consideration. [3]

The basic problem is not so much driven by mass, as it is volume. The most efficient usage of material under orbital loads would be arranged as large, open truss networks. The challenge, however, was to package these structures to efficiently use the volume of the launch vehicle.

### The Need for Large Space Telescopes

In the past decade, NASA and the astronomy community has developed and initiated a visionary plan for expanding our understanding of the universe. This set of astronomical missions meant for the next two decades is known as the Origins Program. The intent of Origins is to probe the universe at resolutions not possible today, with telescopes perhaps 100 or even 1000 times the sensitivity and resolving power of the Hubble Space Telescope (HST). This would be perhaps sufficient resolution to image earth-like planets around nearby stars, detecting the chemical signs of life. It is difficult to imagine a mission with more profound impact.[5,6]

But to realize this vision, NASA needs to construct extremely large telescopes, with perhaps 100 times the collecting area of the Hubble or more. The size of the telescope is driven by three factors: the wavelength of the observation, the required sensitivity or light gathering capability, and the required angular resolution of the observation. For example, infrared (IR) telescopes might require a 30-meter diameter for the same imaging resolution that an ultraviolet/optical (UVO) telescope would require an 8-meter diameter [7].

The Origins vision extends much beyond these sizes. For example, the Terrestrial Planet Finder may well be a 100-meter long interferometer. Other missions beyond that, which would be able to image earth-like planets, would require multiple, 30-50 meter optical or infra-red telescopes separated by thousands of kilometers to form a virtual, interferometric image.

## Main Concept

To this end, this informational proposal advocates the use of telescopes and spacecraft that are partially or fully assembled, tested and integrated on-orbit. Scaling laws indicate that the total structural mass required to achieve a particular level of performance (such as achieving an appropriate first bending mode) will be lower than for the equivalent deployed system. This scenario also leads to a reduction in the number of mechanisms required for a typical astrophysical observatory, thereby reducing launched mass, as well as potential areas for instabilities [8-11]

The challenges and potential of human assembly and maintenance in space has been well documented[12-16]. Using human assisted integration and test in space could reap the same benefits. Complete assembly or a combination of assembly and deployment/unfurling etc, could be used as required by the mission. This would eliminate need for large ground test facilities. Vibration testing could be conducted for the much smaller on-orbit loads instead of launch loads.

As developed more fully in Reference [1], existing deployable concepts are limited in their packaging density. There are advantages offered in packaging the observatory for launch and the range of launch vehicles that become candidates if assembly is considered as an option.

The ability to assemble on-orbit is essentially available for lower Earth Orbit (LEO) now. With some more technological advances, this capability can be a extended to ISS, L2 and beyond.

## REQUIRED TECHNOLOGIES

The following list of preliminary research issues need to be explored in order to reap the many advantages of on-orbit assembly:

### Integrated modeling of optics, structures and control

The integrated modeling of structures, optics and controls eliminates the need for some ground tests. However, in order to get to that point, experimentation comparing ground tests, on-orbit tests and modeling must be accomplished. A number of technical challenges must be overcome to make modeling an effective tool for designers. Computational efficiency must be improved to allow high temporal resolution in the results. The modal content of models must continue to increase to allow accurate description of the surface quality of optics. The number and bandwidth of sensors and actuators must be allowed to increase since it is likely that the real observatories of the future will be replete with them.

### Humans at L2 and beyond

The technology for human assembled spacecraft is already mature. Humans can already begin to assemble spacecraft in lower Earth orbit. However, the next generation of spacecraft, such as NGST and TPF, will be used at points further from LEO, such as the libration points. Therefore, humans will need to be sent to L2 and beyond. Operation at L2 implies that some key technical challenges must be overcome; radiation protection for astronauts, clean and efficient space suits, effective robotic support, space tugs with the capability for rapid transit through radiation belts, efficient propulsion for station keeping at L2, etc.

### Develop more advanced robots

Eventually, assembly, maintenance and repair will be handled autonomously by robots. Advances are being made in this area, but are not ready for full autonomy

### Structural Concepts

Human/robotic assembly potentially provides design freedom not considered before, such as complex hierarchical geometries for telescope structures. Moreover, concepts do not exist that anticipated the extensive developments in lightweight precision structures, optics, and robotics over the last decade, or those anticipated for the next.

The lowest mass telescope structures will be those designed for the miniscule loads on orbit, during operation. In principle, this could be only a few micro-gravities of load, if that is the only load on the structure.

## Precision Low Mass Structural Joints

The practical mass required for the joints of an assembled structure can theoretically be a savings in mass over a deployed structure.

## Degree of Deployment Versus Assembly

Potentially, one could envision construction sequences in which large subassemblies are carried to orbit, partially deployed, and then assembled by humans or robots. The appropriate mix will be determined by the mission requirements, relative costs, and state-of-the-art.

## Passive Structure Versus Active Control

A low mass telescope will probably allow a certain level of structural deformation to occur passively, and then compensate for that deformation through active optical adjustment and/or control.

## On-Orbit Integration and Test

In a real way, the currently planned deployable concepts used, are completely autonomous–though mechanically simple–robots. The risk of autonomy is accommodated by extensive mechanical and optical verification on the ground. This is a large component of the cost of such an approach. It also means these structures are designed for 1-g testing. On-orbit assembly provides the opportunity to accept more initial risk because of the ability to repair components *in situ*. A specific challenge is the thermal management of the observatory in LEO during testing.

## Nanometric Structural Instabilities

Friction in the joints can store strain energy that can be released at nanometer scales of motion. Assembly means there will be many more joints compared to a deployed concept. Engineers have spent the last decade developing deployable optical concepts that nearly eliminate joints so that the joint-driven instability of the telescope falls well within the capability of the active control system.

## Advanced Cleaning Technologies

A main concern with using humans to assemble large telescopes is the possibility of contamination of the optical surfaces. Cleaning technologies are needed to assure that effluents from astronaut suits do not have an adverse impact on the performance of the optics being assembled.

## The Need for Volume Efficiency

The cost of a launch is partly due to the mass, but also due to the volume. If one divides the mass by the volume of existing booster payloads, the average density of most modern payloads is found to be very small (on the order of 65 $kg/m^3$). This reflects the premium placed on volume for spacecraft, in addition to payload mass. As telescope size increases, it is important that concepts are used that evenly expand the use of the mass budget and the volume budget. In other words, the more scalable telescope concepts are those that use nearly equal fractions of the allotted mass and volume, as a function of size.

As developed more fully in Reference [1], existing deployable concepts are limited in their packaging density. The concepts for NGST use a single fold deployment, in which the depth of the structure is constrained by the distance from the hinge line to the payload envelope. The density is relatively low. More compact concepts such as the TRW HARD concept and the Starburst concept generally provide higher density that that of NGST, but have lower stiffness. Assembly would allow both a compact stored volume and a high stiffness. It is possible, for example, to assemble trusses with the frequency of TPF but with a balanced use of mass and volume capacity.[1]

## Combination of humans and robotics

In order to ensure the correct mix of robotics and human involvement, the following ideas need to be addressed:

- Develop an initial set of space observatory task goals (i.e., assemble large mirror, remove/replace avionics box, replace spent propulsion fuel or liquid cryogen, inspect for MOD damage, etc.).
- Break down observatory task goals into potential task primitives and task primitive groups (i.e., activate spring-loaded mechanism, translate small box, mate/demate connectors, etc.)
- Develop an initial set of human-robotic technologies (i.e., EVA-based, telerobotics, autonomous robots, optical cleaning) that accomplish task primitive groups.
- Develop an initial set of metrics (i.e., mass, power, cost, schedule, etc.) to determine optimum human-robotic technologies toward accomplishing task primitive groups

## EVOLUTION OF RELATIVE ROLES OF HUMANS AND MACHINES

The integration of humans and robots for the purpose of building and maintaining spacecraft will be a step-by-step process for many years to come. The relative role will change, depending on the need and function of each mission. Each mission will define a set of human–robotic technologies and their ability to accomplish identified task primitive groups. Very likely the best solution will exploit human presence for specific tasks, telerobotics for others, and, eventually, perhaps even truly autonomous robotics for others. Early missions may start with full human assembly. Later, humans and robots will work together, whether side-by-side, through teleoperation, or simply with the human as an observer. Much later, a spacecraft may be completely assembled by several technologically advanced robots.

In order to make this a reality, the following immediate items are necessary:

- Develop a Catalog of Assembly, Maintenance, and Servicing Task Goals and Primitives on Expected Near-Term Observatory Missions
- Identify Human-Robotic Technologies and Metrics to Accomplish Task Primitives
- Develop Limited Scenarios of Space Observatory Task Primitives through Development of Key Task Groups
- Identify Potential Space Observatory Design Modifications and related Simulations and/or Flight Experiments
- Identify Human-Robotic Technologies and Metrics for the Catalog of Assembly, Maintenance and Servicing Task Primitives

## SCIENCE ENABLED

Currently, the use of assembled telescopes will enable stiffer structures. This in turn will lead to a variety of improvements. These improvements will enable the following Science technologies:

### Increased Aperture Size Will Lead to More Science

Key among the system studies of human assembly will be measures of the mass savings introduced, compared with deployed observatories. These mass savings represent a significant resource that can be applied to increase the size of the aperture of a telescope, for example. In so doing, the mission time required to achieve particular science goals is shortened, and reduce the amount of fuel and cryogen required. These latter effects allow even more aperture increase, or the inclusion of larger, more complex, more capable instruments.

The mass of a space structure can only be rationally determined within the context of the loads for which it is designed. A structure that carries no load need have no mass. In that sense, every space structure is “gossamer” for exactly the loads and conditions in which it is designed to operate. Typical on-orbit loads include gravity gradient, pointing and slew, on-board disturbances (reaction wheels) and thermal loads. Though small, they have a profound effect at optical levels of precision. Of these, all but thermal loads are inertial. That is, they scale with the mass of the structure.

For the most part, the mass is driven by the need to withstand these inertial loads. [4] In this case, the magnitude of the displacement will scale with the ratio of stiffness to mass, or the frequency of the lowest vibration mode of the structure. This is true whether the load is static, quasi-static or dynamic. This is a very powerful design requirement.

### Increased Baseline Will Lead to More Science

A stable structure can also lead to long-baseline interferometry which in turn enables micro and nano-arcsecond imaging/astrometry. Applications include- radio & mm/sub-mm for ultra-low frequency Interferometry, thermal infrared for missions such as Terrestrial Planet Imager; UV/optical/NIR: for SUVONIR;, which will provide visible light planet detection; and X-ray: for grazing incidence (monitor / control at RC)

### Potential Evolution and Re-use of Telescope Components

Current planning practice within NASA and the space science community is to envision distinct spacecraft for different astronomy missions. But when the amount of optic launched into orbit becomes large, one starts to wonder whether it might be possible to reuse this investment at the end of a five-year mission. Construction allows us to consider this.

## SCIENTIFIC/TECHNICAL REFERENCES


1. Lake, M.S. "Launching a 25-Meter Space Telescope: Are Astronauts a Key to the Next Technically Logical Step After NGST?" Presented at the 2001 IEEE Aerospace Conference (IEEE Paper No. 2001-460) Big Sky, Montana, March 10-17, 2001.

2. Nikolayev, A. "Assembler—The Future Profession of an Astronaut" N68-15733. Translated by J. Zygielbaum from *Aviatsiya I Kosmonavtika* No. 2, 1967, pp 45-47

3. Hedgepeth, John M., Mikulas, Martin, M. and MacNeal, Richard H. "Practical Design of Low-Cost Large Space Structures" Aeronautics and Astronautics, October, 1978, pp30-33.

4. Hedgepeth, John M. "Critical Requirements for the Design of Large Space Structures" NASA CR 3484, 1981.

5. OSS Strategic Plan 2000, http://spacescience.nasa.gov/admin/pubs/strategy/2000/index.html

6. McKee, C.F. and Taylor, J.H. (co-chairs) "Astronomy and Astrophysics in the New Millennium" National Research Council, Astronomy and Astrophysics Survey Committee, National Academy Press, 2001.

7. Shull, J.M, Savage, B.D., Morse, J.A., Neff, S.G., Clarke, J.T., Heckman, T., Kinney, A.L., Jenkins, E.B., Dupree, A.K. Baum, S.A., and Hasan, H. "The Emergence of the Modern Universe: Tracing the Cosmic Web" A White Paper of the UV-Optical Working Group (UVOWG). Report for NASA grant NAG5-4312, November, 1999.

8. Lake, M.S., Peterson, L.D., Mikulas, M. M., Hinkle, J.D., Hardaway, L.R., and Heald, J., "Structural Concepts and Mechanics Issues for Ultra-Large Optical Systems" Ultra-Lightweight Space Optics Workshop, Napa, CA, March, 1999.

9. Hardaway, L.M.R. and Peterson, L.D. "Stability and Mechanics of Precision Deployable Structures Under Nanometer Deformation" Doctoral Dissertation, Report No. CU-CAS-00-12, May, 2000.

10. Warren, P. A. and Peterson, L.D., "Sub-Micron Non-Linear Shape Mechanics of Precision Deployable Structures", Ph.D. Thesis, University of Colorado, Report # CU-CAS-96-18, 1996.

11. Hinkle, J. D., and Peterson, L. D., "Frictional Microslip Due to Roughness in Metallic Interfaces at the Nanometer Scale", Ph.D. Dissertation, University of Colorado, Report # CU-CAS-98-12, 1998.

12. Collins, T.J., Fichter, W.B., Adams, R.R., and Javeed, M. "Structural Analysis and Testing of an Erectable Truss for Precision Segmented Reflector Application" NASA Technical Paper 3518, July, 1995.

13. Muller , R. M. "Robotic Assembly of a 20-Meter Space Telescope With Extension to 40-Meter Space Telescopes" February 22, 2000 QSS Group, Inc.

14. Anderson, D. E. and Rockoff, L. M., "EVA/Telerobotic Cooperation for Aerobrake Assembly," McDonnell Douglas, MDSSC H5685, AIAA 903678, Presented at the AIAA Space Programs and Technologies Conference, September 1990.

15. Anderson, D. E. and Rockoff, L. M., "Telerobotics As An EVA Tool", McDonnell Douglas Space Systems Company MDC H5686, SAE 901397, presented at the 20th International Conference on Environmental Systems, Williamsburg, July 1990.

16. Heard, W. L., Jr. and Lake, M. S.: “Neutral Buoyancy Evaluation of Extravehicular Activity Assembly of a Large Precision Reflector.” *AIAA Journal of Spacecraft and Rockets*, Vol. 31, No. 4, July-August 1994.